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Radiation Driven Capsules for Fast Ignition

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Radiation Driven Capsules for Fast Ignition

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The energy required to ignite compressed deuterium-tritium fuel is a strong function of the fuel density. Through a series of detailed numerical simulations, peak fuel densities have been calculated as a function of the peak radiation drive temperature. Note that the time dependence of the radiation temperature (pulse shaping) has been optimized to obtain maximum density for each scaling point. A simple analytic scaling is developed, which agrees well with the numerical results. These scaling results are then used to obtain the required ignition energy as a function of peak drive temperature .

I. Introduction

The fast ignitor concept[1] separates the capsule compression from the ignition of the hot spot. This reduces some of the constraints on the implosion system and in principle, results in higher gain capsules. Near isentropic compression is required to obtain efficient implosions to high density. The fuel density is a key figure of merit for the fast ignitor, since the ignition energy scales[2] as $E_{ig} = 700\rho^{-1.85}$ MJ. A series of LASNEX[3] simulations have been performed to determine peak density as a function of the peak radiation temperature. These results are coupled to the fast ignition scaling to yield a lower bound on the ignition energy as a function of the peak radiation drive.

II. Simulations

In this study we chose a simple capsule design as shown in Fig. 1a. The capsule geometry is defined by its initial outer radius, R_{cap}, the aspect ratio $A_R = \dfrac{R_{cap}}{R_{cap} - R_{inner}}$, and the fuel fraction defined as the ratio of the fuel thickness to the total capsule thickness, $F_F = \dfrac{R_{fuel} - R_{inner}}{R_{cap} - R_{inner}}$. Optimal performance requires maximizing the fuel fraction without the radiation burning through the ablator. Adding a small fraction (0.0025 atomic) of Bromine to the plastic ablator helps in this reqard.

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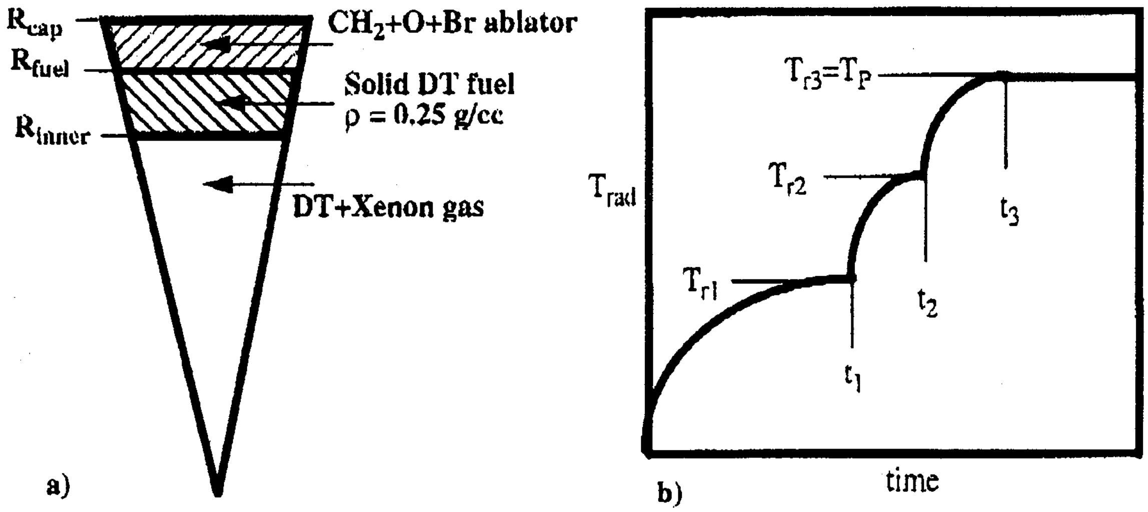

Figure 1. Schematic of capsule design a) and pulse shape b)

Some oxygen (~0.05 atomic) naturally occurs in plastic and was included in the simulations. The central region was assumed to have deuterium-tritium (DT) gas at a density of $1.\mathrm{x}10^{-4}$ g/cc, consistent with the vapor pressure for the DT ice at a temperature that would allow β layering to smooth the inner surface. The addition of a small atomic fraction ($1.2\mathrm{x}10^{-4}$) of Xenon was found to significantly increase the capsule performance though radiative cooling of this region during the compression. This should not affect the burn of the DT shell even if it was completely mixed into the shell because the total Xenon mass is a very small fraction of the DT mass.

The capsules were driven by a radiation drive assumed to be Planckian with a temperature that is time dependent. A number of "pulse shapes" have been tried. The best results were obtained by the generic profile shown in Fig. 1b. Here the radiation temperature is increased in three steps, which generate three shock waves that compress the capsule and accelerate it inward. Marginally better performance could be obtained by using more shock waves, but at a significant increases in the complexity of optimizing the profile. The j^{th} temperature step was determined by the function $T_{rad} = T_{r(j-1)} + T_{rj}[1-(t_{j+1}-t)^P]$. The value of P was varied from 2 to 8. There appears to be a degradation in performance for large values due to the abrupt change in drive temperature. We used P=2 for the results reported here. A typical final fuel configuration is shown in Fig. 2a

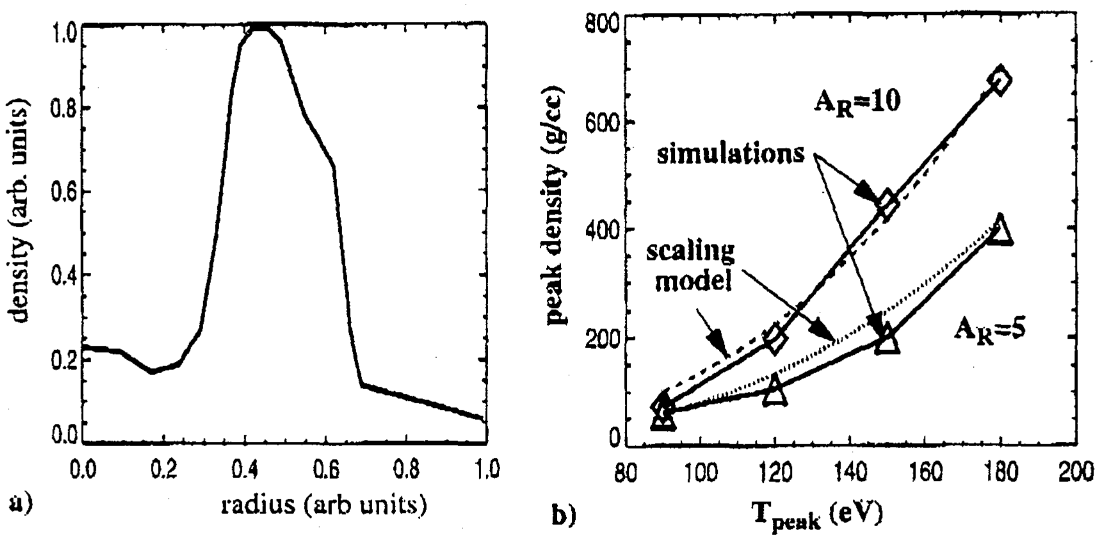

Figure 2. Final fuel density plotted as a function of radius a) and the density as a function of peak drive temperature b). The diamonds are for A_R=10 and the triangles are for A_R=5.

The results clearly show that the fuel configuration is a hollow shell rather than a solid ball as sometimes assumed. This effect would be even more pronounced if the inner gas were not doped with Xenon. This final configuration is qualitatively the same if the central region is assumed to be vacuum. Several simulations were performed to find the conditions necessary for propagating burn around this shell. The results indicate that the condition $\int \rho\, dr \geq 1$ g/cm^2 must be satisfied. Capsules were designed to satisfy this condition and optimized for peak density by varying the capsule parameters. The peak density is a strong function of the peak drive temperature as seen in Fig. 2b.

III. Analytic scaling

A similarity solution describing the implosion of a hollow spherical gas shell with γ=5/3 exists, from which the peak stagnation density has been found[4] to be $\rho_s \approx 2.4\rho_0 M^{3/2}$, where ρ_0 is the density of the shell before stagnation and M is the Mach number of the implosion. The speed of sound is $c_s^2 = \dfrac{\gamma P_0}{\rho_0}$, where P_0 is the pressure within the shell, which should be approximately equal to the ablation pressure given by the relation[5] $P_{abl} \approx 3T_p^{3.5}$ MB, where T_P is the peak radiation drive temperature in units of 100 eV. The pressure/density relationship for zero temperature given by Sesame tables[6] is approximately $P = 0.24\rho^{2.2}$. Combining these equations we obtain $\rho_s \approx 5.2\times10^{-9}T_P^{0.17}v^{3/2}$. The implosion of the shell is governed by Newton's law, $m\frac{d^2r}{dt^2} = 4\pi r^2 P_{abl}$, which can be integrated if we assume constant mass and ablation pressure. Since the shell does not move much during the rising portion of the radiation pulse, we use the peak radiation temperature to calculate P_{abl}. We estimate the average mass to be $\bar{m} \approx 4\pi r_0^3 \rho_{DT} A_R^{-1}$ and obtain the implosion velocity given by the formula $v = 2.8\times10^6 T_P^{1.75} A_R^{0.5}$ cm/s. Substitution into our previous expression for the stagnation density yields the result $\rho_s \approx 24 A_R^{0.75} T_P^{2.8}$ g/cc. This scaling is compared to the optimized simulation results in Fig 2b. The agreement is surprising since the equation of state for DT deviates significantly from a gas with a constant $\gamma = 5/3$. The simulations indicate that the maximum average density though the shell is approximately $\bar{\rho} \approx 0.34\rho_{peak}A_R^{1/4}$. Using this we obtain a scaling for the ignition energy $E_{ign} \approx 1.4\times10^4 A_R^{-1.85} T_P^{-5.2}$ kJ, which is a very strong function of the drive temperature.

IV. Discussion

The ignition energy scaling suggests that very high drive temperatures are desirable for fast ignition. However, there are two potential problems with driving the fuel to very high densities. First, the fuel disassembly time decreases with density. Defining Δt_g as the time that the fuel density remains above 80% of the peak (ignition energy varies by factor of 2) we find that $\Delta t_g \approx 303\rho^{-4/3}$ ns. As an example, the timing between the fast laser and the implosion would have to be better than 30 ps for a density of 1000 g/cc. Second, the laser intensity scales roughly as $I_{laser} > \frac{8\times10^{19}}{\eta}\left(\frac{\rho}{100}\right)^{1.15}$ watts/cm^2, where η is the efficiency. This could lead to generating electrons that are too energetic for efficient coupling.

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